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Super-light SL-Deck elements with fixed end connections

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Abstract

Super-light structures combining light and strong concrete are invented by the author at the Technical University of Denmark and commercialized by the spin-out company Abeo Ltd.
The first product is the SL-Deck element that represents a number of strong improvements to the building industry among which improved sound insulation, low weight, low CO_2 emission, 4 hour fire resistance, improved flexibility with respect to holes, services, curved edges, conical shapes, cross-reinforcements, included beams and edge stringers, balcony solutions, hung down elements, leaf-connections, and long spans due to low weight and due to possibilities of continuous elements and fixed end connections.
A new machine is constructed producing the elements and BIM software is developed optimizing the structures, the production, and the logistics and running the machine.
New production lines are established and a number of buildings are made from 2014 applying the deck element.
The paper describes the deck element and experiences from implementing the technology and innovative details from the first building projects are presented.
All the above mentioned benefits are applied to a wide extent in the first building projects leading to considerable savings of time and costs and opening up new possibilities for architects and users.
Furthermore, the paper describes full-scale test results with new fixed end connections between decks and walls and between decks and columns in facades giving more possibilities to applications as for example placement of columns independent on deck element subdivision and avoiding beams in facades.

Keywords: Super-Light structures, Deck elements, Flexibility, Span width, Fixed end connections, Sound insulation, Fire resistance

1 Introduction

Super-Light structures were invented at the Technical University of Denmark (DTU) by the author in 2008, and Pearl-Chain Technology in 2009 (Hertz 2009). The technologies were patented (Hertz 2010) and a start-up company Abeo Ltd. was founded in 2010. The same year the company won the Clean Tech Open competition (World championship in clean technology for start-up companies) in San Francisco because of the CO_2 saving potential of the new concrete structures (Byrne 2010).

The first Super-Light product developed to be mass-produced was the SL-Deck. A prototype production was made in 2011 and full-scale tested for load-bearing capacity (Halldorsson 2012) and for sound insulation, step noise transmission, sound damping, and fire resistance (Hertz & al 2014). The first prototype production was used for suspended pedestrian bridges in building 324 at DTU.

Simultaneously, the slab elements were developed further. Full-scale tests were made, and a new production technology was developed by the company including a machine to cast the light weight aggregate concrete and automation software and a multitude of new details.

In 2014 the first mass-production was started of the SL-Deck, and it soon proved its benefits in actual buildings of extraordinary shapes and at the same time full-scale tests were made of fixed-end connections, and Pearl-Chain arches and the first actual Pearl-Chain arch bridge is constructed.

2 Basics of Super-Light structures and SL-Decks

The concept of Super-Light structures was inspired by the Roman structures, where horizontal layers of concrete varying from heavy qualities at the bottom of a cupola to ultra light concrete at the top made it possible to increase the span-width.

In a Super-Light structure, the engineer places a strong heavy concrete, where the forces should be, and fills out the remaining shape of the structure with a light-weight concrete – usually a light weight aggregate concrete that also stabilizes the strong concrete and protects it from impact and fire and in addition a good sound insulation is obtained because of the internal loss of the combination of materials reducing sound energy to heat (Lauricina 2010, Bagger & Hertz 2010).

By means of this, weight can be saved, span-widths increased, flexible elements can be produced that simplify the building process on site, and where time and materials consume and CO_2 emissions are reduced (Bagger & Hertz 2011, Castberg & Hertz 2012).

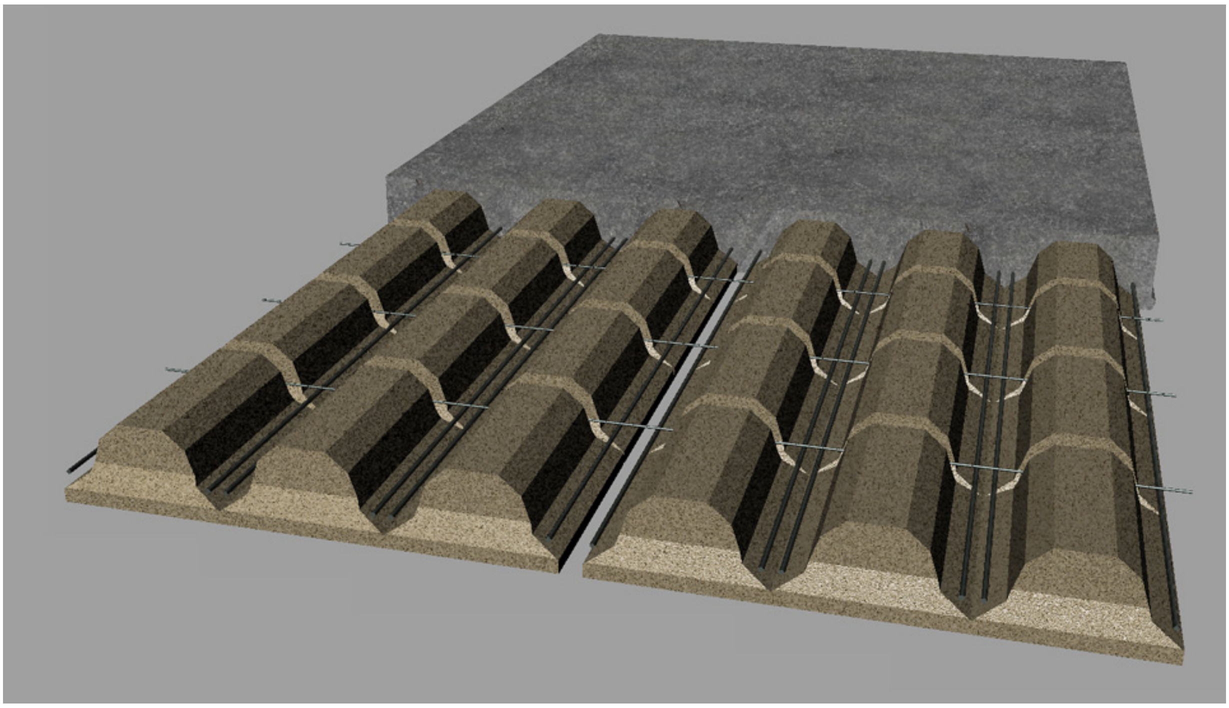

Fig. 1 Principle of a 2.4 m wide SL-Deck element

The SL-Deck consists of a bottom layer of light weight aggregate concrete with density 700 kg/m^3 upon which a number of light weight aggregate concrete blocks are placed (Fig. 1 and 2). The light weight aggregate concrete is produced by a patented automatic machine on 100 m tracks. Pretensioned tendons are located between the blocks and slack reinforcement is placed across. On top is cast an ordinary 55 MPa plastic concrete before the light weight aggregate concrete is fully cured. The elements are separated by mould bars when casting leaving a massive zone with no blocks of a length of at least 200 mm at each end of each element.

Furthermore, massive zones are placed where continuous deck elements are supported on walls.

The massive zones improve the shear and anchorage properties without increasing the moment loads since the extra weight is close to the supports, and they provide good properties for the joints between deck and walls and ensure the function of the walls as shear plates stabilizing the building.

For domestic buildings the casting machine usually places a white mortar at the track before casting the light weight aggregate in order to give a smooth bottom surface. This is omitted in case the customer wants an effective sound damping with properties, which as a function of frequency are equal to those of wood-wool sound damping plates (Fig.3).

Fig. 2 SL-Deck Element illustrating the construction by visible light weight aggregate concrete blocks, pretensioned tendons and cross reinforcement.

Fig. 3 SL-Deck elements with blade connections and a sound damping part of bottom surface for the class rooms at Old Hellerup High School 2014. Architect BIG.

New details and assemblies are developed such as in-plane blade connections (Fig. 4), fixings for balconies, rounded shapes (Fig. 5), inlaid installations, inlaid beams, and fixed-end connections to walls and other deck elements.

Fig. 4 SL-Deck element with blade connection supporting it on the side of another SL-Deck element.

Fig. 5 Wedge shaped SL-Deck elements with rounded ends making a circular building for Innovest 2014. Architect Aarstiderne.

In addition, the Pearl-chain technology was developed for arch bridges and vaults, and the SL-Deck was prepared for constituting elements in these arches by enclosing space for post-tension cable ducts and possibilities of inclined ends of the elements (Halding 2014, Hertz & Halding 2014).

Prototypes of SL-deck elements have been tested for mechanical action, sound, and fire impact during the development period, and in 2014 new accredited tests have been made proving that a 220 mm thick SL-deck of 340 kg/m^2 fulfills the new severe Danish sound abatement requirements for having a sound insulation of 58 dB (should be larger than 55 dB) and step noise level of 47 dB (should be less than 53 dB) (Fig. 6). These results are better than what can be obtained for similar elements of plain concrete. One reason is that sound is reduced to heat by different oscillations of the different concrete materials in the deck element (Christensen & al. 2011).

The fire test demonstrates that the new SL-deck has a 240 min standard fire resistance (Fig. 7) on a 6 m furnace and loaded in bending as if it was loaded with dead load and an office- or domestic load at a free simply supported span of 9 m. This means that the shear forces at this test was equal to those of a deck of a span of 9*(9/6) = 13.5 m. If the ultimate positive moment capacity is reached, such a span would require a negative moment at the fixed end connections of $(13.5/9)^2 - 1 = 1.25$ times the ultimate positive moment of the SL-Deck exposed to fire. This means that the fire test also demonstrates the hot shear capacity for 220 mm thick 13.5 m long SL-Decks that might be obtained with application of fixed end connections.

Fig. 6 SL-Deck in accredited sound insulation and step noise test.

Fig. 7 SL-Deck after 240 min accredited fire test.

3 Fixed end connections

The SL-Deck has already a possibility for obtaining longer span widths than deck elements made of a single type of concrete, because it fulfils the sound insulation requirements at a weight of only 350 kg/m^2, where other elements need 440 kg/m^2, which is significant since the weight of the element usually is the main load in a domestic building.

A further increase of the span-with can be obtained by application of fixed end connections.

Where a deck element is continuous over a wall the vertical compression reaction of the wall above on the massive zone of the deck element at the joint is taken into account and if needed supplemented by vertical bolts with anchor plates on the massive zone or a traditional stirrup connections to the wall above. Alternatively, vertical post tensioning may be provided to establish a suitable compression in the shear wall and at the joint.

If an end of a deck element is supported on a wall creating a fixed end connection or if it should be joined with another deck element to form a continuous slab, one solution is at the factory to cast the element with grooves at the top for placing slack reinforcing bars interacting with the pretentioned tendons in the top of the element. The grooves are provided with recesses shaped as squares inclined 45 degrees with the axis of the groove as seen in Fig. 8. At the building site the reinforcing bars are placed in the grooves and the grooves are cast out (Fig. 14 -16). These operations are typically made as a part of the operation of reinforcing and casting the joints between the elements.

The 45 degree inclined recesses are easier to cast out than if they were rectangular to the groove axis; but the main reason for the design is to improve the anchorage of the bar. This is seen from the ultimate limit cone model for anchorage stresses introduced in Hertz 1982.

Fig. 8 Grooves for slack reinforcement at top of a SL-deck for a joint with another element.

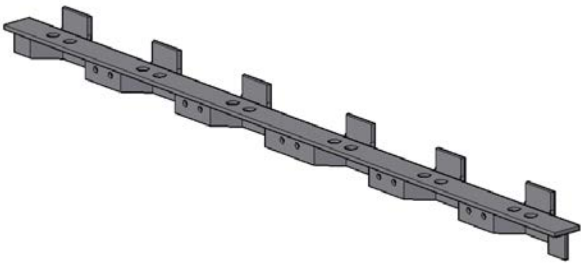

Fig. 9 Patented steel bracket in the tested fixed end joint.

4 Test set-up

One version of a fixed end connection was tested by Tahtah & Al-Nema 2014, where 3 full-scale tests were made of a frame corner with a steel bracket in the joint between deck and wall as shown at fig. 9. It has a vertical folded part to which the horizontal deformed bars in grooves of the deck element are fixed with nuts before the joint is cast out. Then a horizontal flat steel part was placed on top of the cast joint to which the vertical reinforcement of the wall was connected by nuts.

When the joint is subjected to tension from the slack top reinforcement in the grooves of the deck element and compression from the bottom part of the massive zone, these forces are exchanged with an inclined compression force in the joint acting on the steel bracket and a vertical tension in the wall reinforcement near the outer surface and acting on the compression forces at the bottom of the deck and the near the inner surface of the wall (Fig. 13).

The geometry before casting the joint is seen at fig.ure 11, and figure 10 illustrates the relative size of the cantilever of the test specimens compared to the wall.

Fig. 10 Relative dimensions of wall and cantilevered deck element where only the wall is supported by the test rig.

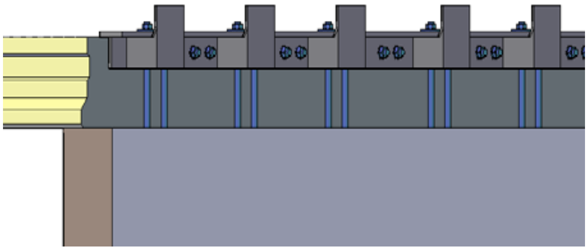

Fig. 11 Connection seen inclined before casting.

Figure 12 shows stresses in the steel bracket found by a FEM analyses confirming the hand calculated estimate from the design of the bracket.

Figure 17 shows the test rig with moment resistant support of the wall element, a bridge with hydraulic jacks and a temporary rig to support the end of the deck for oscillation tests. This was removed for ultimate bending test of the fixed end connection.

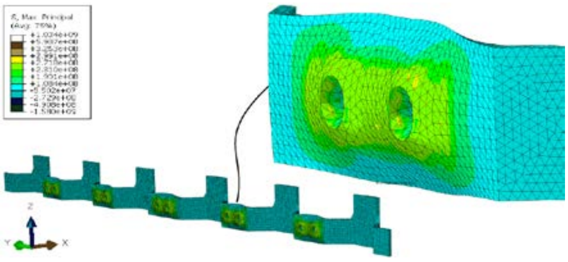

Fig. 12 Stresses from FEM analysis.

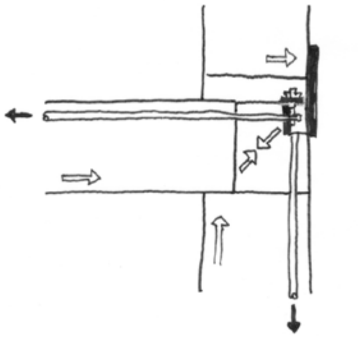

Fig. 13 Forces in cross between walls and fixed end supported deck.

Figure 14 shows the joint and the top grooves before casting and mounting the top steel plate, and figure 15 and 16 show casting of the joint and groove. Stirrups in the grooves improve the anchorage of the slack reinforcing bars and the exchange of forces with the pre-tensioned tendons at the top of the slab element.

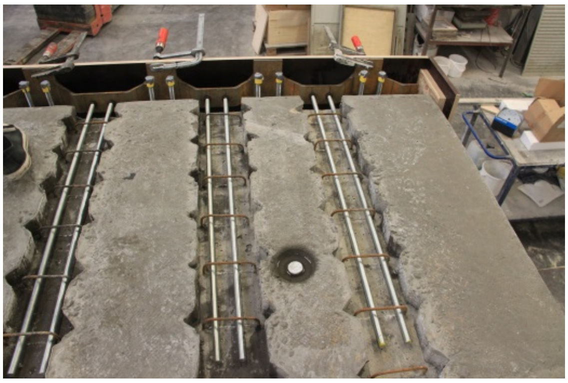

Fig. 14 Grooves at top with reinforcement.

Fig. 15 Casting of joint and top grooves.

Fig. 16 Cast out joint and grooves.

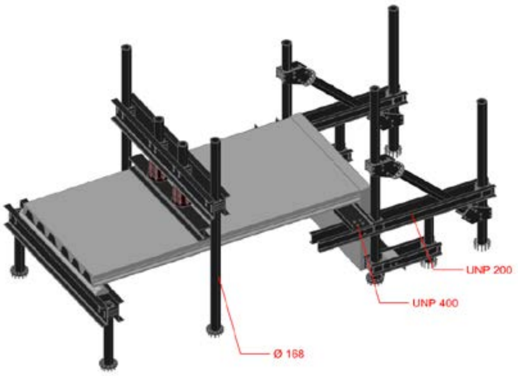

Fig. 17 Test rig with wall and cantilevered deck.

5 Tests

Figure 18 and 19 show handling of test specimens each consisting of a 2400 mm wide and 200 mm thick wall element with fixed connection to a 220 mm thick SL-deck element.

This also illustrates that connected elements can be lifted in place as frame corners or as full frames, if they for some reason should not be assembled on site, which will be the usual case, since that would be easier to transport to the building site, and the grooves around the slab elements should be cast out anyway.

Fig. 18 Connected walls and decks at test rig.

Fig. 19 Lifting of frame corner test specimen

Fig. 20 Broken joint.

Fig. 21 Broken joint.

The deck elements were 2400 mm wide, 220 mm thick and 2 of them (A and B) were 5000 mm long and C was 3500 mm. The wall elements were all 2400 mm wide, 200 mm thick.

The vertical and horizontal reinforcement in the joint was for the test purpose deliberately less than that for the wall and deck elements respectively. From the wall it was 12 Y 16 bars with cover 55 mm to the centre line from the backside of the wall. From the deck it was 10 Y 16 with cover 37.5 mm. Each Y 16 bar has a characteristic yield strength at the cut thread bolted end of 94 kN that would give the joint a characteristic moment capacity of 107 kNm.

Compressive strength and E-modulus was determined at the time of testing by means of 3 cylinders cast when casting the joint and 3 when casting the elements. A compressive strength of approximately 50 MPa was found for the joint concrete and 60 MPa for the elements at time of the test. These values were applied in the theoretical calculations. The mean value of the E-modulus for the elements was found to be 33 GPa.

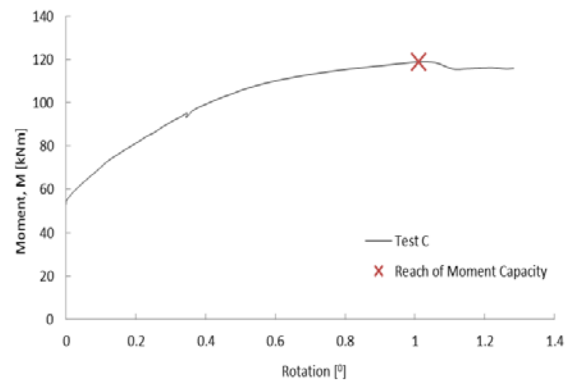

Fig. 22 Moment versus rotation for test C.

Fig. 23 Cracks at top of joint.

The ultimate bending capacity was measured as 118 kNm in test A and B and 119 kNm in C.

Investigations of the crack formations during the tests showed that the failure of the connection was caused by the elongation and yielding of the horizontal bars. This was evident as cracks were formed between the SL-Deck and the connection followed by a diagonal crack formation where the joint rotated about the compression zone in the bottom of the slab. The bracket steel was not deformed after the test.

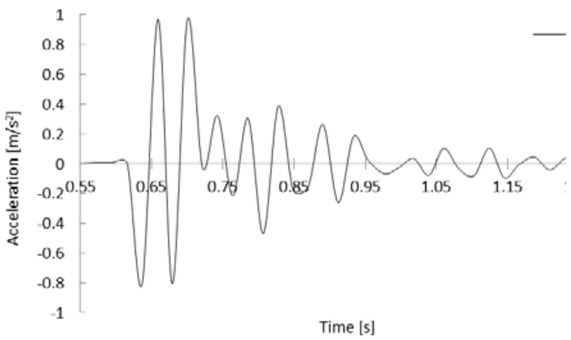

Fig. 24 Acceleration time domain for test A.

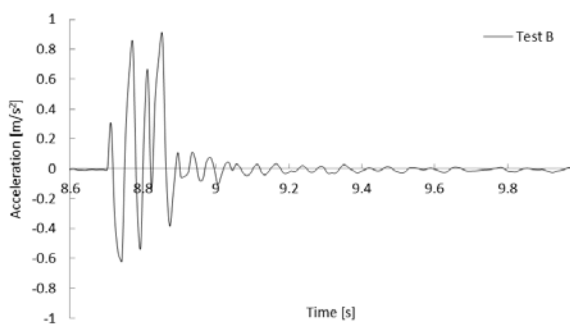

Fig. 25 Acceleration time domain for test B.

Before the moment capacity tests the eigenfrequencies were measured for specimens A and B with 5 m span and a temporary simple support at the free end. They were found to be 23.7 and 24.4 Hz, and could be calculated to be 20.7 Hz using an E-modulus of 50 GPa for the concrete as recommended by the Danish Concrete Element Society. This is therefore seen to be on the safe side for the present structure and justified compared to the value 16.8 Hz that would be found by calculation if the measured modulus of elasticity of 33 GPa was applied.

6 Conclusions

The super-light SL-Deck was introduced on the Danish market in 2014 and represents an improvement with respect to sound insulation, fire resistance compared to deck elements of the same weight. The first construction projects prove an increased flexibility due to a multitude of new possible connections and shapes. Span-widths can be increased by low weight for the same sound insulation and the possible application of fixed end joints. A test series of frame corners with 220 mm decks and 200 mm walls illustrates the detailed function of one possible fixed end joint geometry, and oscillation tests show that an E modulus of 50 GPa may be applied for calculation of the eigenfrequencies.

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